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# Combining multiple proxies to investigate water table fluctuations in wetlands: A case study from the Rėkyva wetland complex, Lithuania

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ABSTRACT

The impact climate and land-use changes have on the hydrological conditions in peat bogs and lakes is often complex, but of great importance for the carbon budget and biodiversity in these ecosystems. Links and feedbacks between raised bog water table depth, lake level, net precipitation, hydrometeorological indices, and radial tree growth have been studied and identified in the Rėkyva wetland complex, Lithuania. Moreover, several statistically significant correlations between raised bog water table depths, lake level, local river runoff, and tree growth were observed. The changes of raised bog water table, lake level, and tree growth show synchronous trends despite variations in the absolute values. Our results show decreasing water table in the Rėkyva wetland complex over the last 100 years, especially in the middle of the 20th century. This study also shows a potential for reconstructing water table fluctuations in wetland complexes using multi-indicator approaches. Our observations and reconstruction show consistency with several regional studies and reconstructions of moisture variations in Baltic raised bogs, at least for periods without strong anthropogenic influences.

## 1. Introduction

Peatlands provide ecosystem services as water reservoirs, key habitats with high biodiversity, and have an essential influence on the global carbon cycle (MacDonald et al., 2006; Limpens et al., 2008). Water table fluctuations may, however, have severe consequences for the vegetation, biodiversity and ultimately the carbon budget for peatland ecosystems. Because of hydrological lags and feedback effects in peatlands, we still lack essential knowledge on what impacts environmental changes have on hydrology and associated carbon budget in peatlands (Bridgham et al., 1995; Charman, 2007; Bridgham et al., 2008; Charman et al., 2009; Waddington et al., 2015). Peatlands may also play an important role in storing water during intense precipitation and flooding events (Bullock and Acreman, 2003; Acreman and Holden, 2013), in controlling river base flow (Bourgault et al., 2014), and in maintaining groundwater resources (Fraser et al., 2001). The importance of studying peatland ecosystem processes should therefore not be underestimated.

About 12.3% of the Baltic countries are covered by peatlands (Joosten et al., 2017). Various types of peatlands (e.g. raised bogs) have developed in the undulating landscape that was formed during the last deglaciation (Van der Schaaf, 1999). Water table fluctuations in peatlands are foremost controlled by precipitation minus evapotranspiration, and therefore sensitive to environmental and climatic changes (Sollid and Sørbel, 1998). In addition, peat formation as well as decomposition, and thus greenhouse gas emissions, are linked to the moisture status of peatlands (Korhola et al., 1996; Holden et al., 2004; Franzén, 2006). The emission of greenhouse gases may increase during dry periods, whereas peatlands primarily act as carbon sinks during wet periods (Waddington et al., 1998; Strack et al., 2008; Robroek et al., 2009). Accurate long-term reconstructions of water table fluctuations and moisture status in peatlands are thus essential for an improved understanding of past climatic variations, and to increase our knowledge of peat formation processes.

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Over the last century, agriculture, forestry and various types of infrastructure projects have affected the majority of all peatlands in the Baltic countries, and consequently water level and water storage capacity has been affected. Drainage projects may have severe impact on water quality and resources. Moreover, drainage and agricultural utilization of peat may change on the greenhouse gas balance and vegetation successions of the peatlands (Waddington and Price, 2000; Holden et al., 2004; Price et al., 2005; Oleszczuk et al., 2008). Despite the link between hydrology and carbon sequestration in peatlands, we often lack continuous long-term (decadal or longer) monitoring data measuring water table fluctuations in peatlands. We will therefore use meteorological data (precipitation and net precipitation), hydrological data (short-term water table fluctuations series and long-term river runoff series), and tree-ring data from the Rėkyva wetland complex, Lithuania. We will compare (i) water table fluctuations and levels in different parts of the Rėkyva raised bog and the seepage lake, (ii) relations between the net precipitation and water table changes in the raised bog and the seepage lake, (iii) relations between the river runoff and water table in the raised bog and the seepage lake, and (iv) relations between the radial tree growth and hydrometeorological records (precipitation, net precipitation, river runoff), with the aim to find relations between the parameters, and in an attempt to extend the hydrological records from wetland and peatland complexes beyond the monitoring records.

## 2. Study area, data and methods

### 2.1. Study site

The Rėkyva wetland complex is 3787 ha in size and located about 140 km east from the Baltic Sea in north-central Lithuania (Fig. 1). The wetland complex is located in watershed of the Venta, Mūša, and Dubysa rivers (Fig. 1A–B), and consists of the Rėkyva seepage lake (1179 ha), a peat harvest area (566 ha) and mires (2042 ha), of which 59% are fens and the remaining 41% raised bogs (Fig. 1C). The lakes and wetlands provide a vertical leakage to aquifers, yet receive no inflow from streams or ground water. Such systems are called bogs or bog lakes and they receive their water supply from runoff and precipitation (Kasenow, 2001). The water supply in the Rėkyva raised bog comes from precipitation, but more than two-thirds of the water is lost due to evapotranspiration. Other ways of water loss are through groundwater discharge towards Rėkyva Lake and towards the peat harvest area draining ditches – drainage divide separates raised bog into two parts located in different catchments (Monitoring report, 2017). A small amount of water seeps into sandy loam beneath the peat. This seepage water has a highest impact on the minimal runoff of rivers draining Rėkyva wetland complex. Thus, water storage and runoff from raised bog most depends on difference between precipitation and evapotranspiration. The main part of the water entering the Rėkyva Lake comes from precipitation falling directly onto the lake's surface, whereas groundwater recharging from the lake catchment only cause a small part of the entering water. The main loss of water is due to evaporation from the lake and only the small part of water losses depends on the lake water level and discharge. The water budget in the lake and the raised bog is therefore similar, which indicate that there might be a close relation between water table in the lake and bog areas in the wetland complex (Monitoring report, 2017).

The degraded raised bog still capable of natural regeneration (Annex I Habitats Directive habitat code 7120) is situated in the area between the lake and the peat harvest area. Scots pine (*Pinus sylvestris* L.) dominates the wood vegetation, and *Rhododendron tomentosum*, *Calluna vulgaris* and *Vaccinium uliginosum* are present in the shrubs layer. *Eriophorum vaginatum* and *Melampyrum pratense* from herbaceous plants occur in some places. The moss layer is dominated by *Sphagnum magellanicum, S. capillifolium,* and *S. angustifolium*, but *Bryidae* species replace *Sphagnum* in dryer places close to the peat harvest area.

The thickness of the organic layers varies from 3.5 to 8 m in the area between the Rėkyva Lake and the peat harvest area, with maximum thickness in the watershed between the lake and peat harvest area catchments. The layers consist of slightly decomposed *Sphagnum* peat with the stumps of subfossil pines. The pH of the peat reaches from 4.5 to 5.7. Hydraulic conductivity of peat surface layer reaches 0.15–0.17 m/day in semi-pristine part (Rėkyva Lake catchment) and 0.06–0.08 m/day in drained part (peat harvest area catchment) of the raised bog. Sandy loam layer with elevation 125.0–128.5 m a.s.l. is found beneath the peat layer.

According to historical maps (1840 and 1920), the Rėkyva wetland complex was semi-pristine and the Rėkyva Lake had neither inflows nor outflows until the early 20th century. The lake, with the exception of its eastern coast, is surrounded by raised bogs, with narrow fen strips connecting the lake with rivulet draining the south-western edge of the wetlands complex (Fig. 1C). The surface of the fens was a natural overspill restricting runoff from the lake into the fen during dry years. During periods of rising water table, however, surface water of the Rėkyva Lake periodically flew towards the edge of the wetland. The Rėkyva wetland complex and the hydrographic network of its surroundings were changed from the late 1930s to the late 1950s through the creation of drainage ditches and weirs in the south-western and north-eastern parts of Rėkyva Lake. Water was extracted from the Rėkyva Lake for electrical power and industrial needs from the late 1940s to the late 1970s (Table 1).

### 2.2. Material and methods

To study and reconstruct water table fluctuations in the Rėkyva raised bog, we used long term meteorological and hydrological records from the Lithuanian Hydrometeorological Service (Šiauliai weather station, Rėkyva Lake and rivers' gauging stations), as well as data from Rėkyva wetland complex monitoring network (Rėkyva weather station and raised bog water table measuring wells), where measurements were carried out by study authors in 2011–2017 (Fig. 1). Precipitation and air temperature has been measured at Šiauliai weather station (WS), 11 km north from the Rėkyva wetland complex, since 1925. Furthermore, local air temperature and precipitation records from the peat harvest area at Rėkyva WS have been used for the years 2011–2017. According to the seven-year measurement series (2011–2017) from Rėkyva WS, we observe 1 to 4% higher annual precipitation totals as compared to the values recorded at the Šiauliai WS. By contrast, differences in annual or monthly mean temperatures among the WS stations were relatively small, but daily air temperature (mean, maximum, minimum) at Rėkyva WS is usually slightly higher than at Šiauliai WS.

Runoff at the Dubysa, Venta and Mūša rivers has been monitored by gauging stations (GS) located between 40 and 70 km from the Rėkyva wetland complex: Lyduvėnai GS (Dubysa River, 40 km from Rėkyva wetland), Papilė GS (Venta River, 45 km), and Ustukiai GS (Mūša River, 70 km). Before land reclamation, excess water from Rėkyva wetland flowed to Dubysa River, but since 1946 the water runs off in the Mūša River. Measurements data exist since 1933 at Lyduvėnai and Papilė GSs and since 1957 at Ustukiai GS. Lyduvėnai GS was selected for further analysis, because this is the nearest station with the longest data set, representing the water regime of natural outflow of Rėkyva wetland complex.

Rėkyva Lake water level has been monitored by Rėkyva GS during several periods: in 1951–1978 and 2004–2007 manual measurements were performed, while in 2008–2017 level logger was used to record the lake water level data.

Monitoring of water table in four water table measuring wells (WTW) was performed in 2011–2017. The WTW1 and WTW2 are located in Rėkyva lake catchment (semi-pristine part of raised bog), while WTW3 and WTW4 – in the peat harvest area catchment (drained part of raised bog). *Sphagnum magellanicum* and bog pines dominate near WTW1, WTW2, and WTW3, while *Rhododendron tomentosum*, *Calluna*

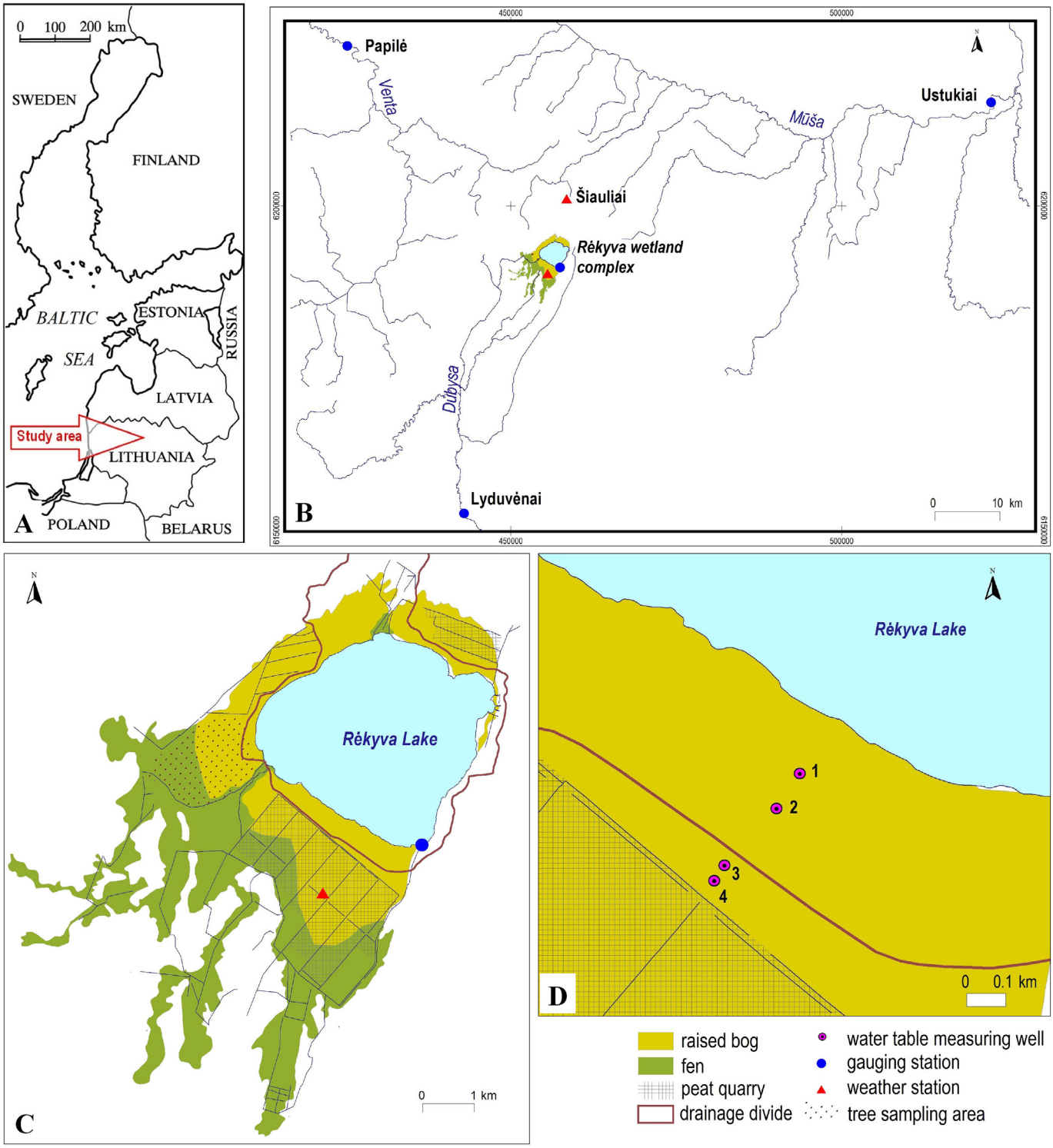


**Fig. 1.** Location of the study area and hydro-meteorological network.

*vulgaris*, *Vaccinium uliginosum* and non-bog forms of pines are present near the WTW4. The range of absolute position of water table is 131.32–131.76 m a.s.l. in WTW1, 133.40–133.79 m a.s.l. in WTW2, 133.31–133.68 m a.s.l. in WTW3, and 132.49–132.90 m a.s.l. in WTW4.

Due to bog vegetation growth and subsidence of upper peat layer surface of raised bog has no constant position and varies throughout the year. Our measurements indicate that the bog surface can change within ± 7 cm per year (Taminskas et al., 2018). It is therefore difficult to determine the depth of the bog water table without measuring the water table and surface elevation at the same time. Therefore, peatland hydrological studies commonly use the absolute position of the water table on m a.s.l., which shows trends and amplitudes of water table changes, but less suitable for solving ecohydrological problems. The diversity of the vegetation, the habitat structure, the conditions for the growth of bog trees and even the surface change depend on the depth of the water table. However, the lack of data on bog surface elevation still prevents wider analysis and use of water table depth indicators.

To add proxy data which can offer complementary information

**Table 1**
Anthropogenic impact on the Rėkyva Lake.

| Period | Hydrological conditions | |
|---|---|---|
| | Natural controls of water level | Water level regulation |
| Until the late 1930s | Semi-pristine lake, no effluents and water abstraction. | |
| Late 1930s–late 1950s | Effluent ditches in the SW and NE parts of lake. Semi-pristine lake, no weirs installed in diches. | |
| Early 1960s–late 1970s | | SW ditch dammed (no outflow). Adjustable weir in NE ditch. Large water abstraction |
| Late 1970s–1992 | Not adjustable (fixed height) weir in the NE ditch. No water abstraction. | |
| From 1992 | The weir crest heightened about 12 cm in NE ditch. No water abstraction. | |

about past water table fluctuations in the wetland complex, tree-ring width (TRW) data from moisture-sensitive pine trees from the Rėkyva wetland complex were used. The raw TRW series cover the period 1834–2013, and have been described in detail by Edvardsson et al. (2015a). To minimize the influence of non-climatic variations and trends related to tree age and geometry, TRW data were standardised and transformed into dimensionless indices using the ARSTAN_41d software (Cook and Krusic, 2006).

We used the basic Thornthwaite equation to evaluate potential evapotranspiration (Thornthwaite, 1948). The difference between precipitation (P) and evapotranspiration (PET) for the month (net precipitation) provides a simple measure of the water surplus or deficit for the analysed month (Vicente-Serrano et al., 2010). Annual water surplus or deficit at Rėkyva Lake and the raised bog was calculated using annual precipitation and annual potential evapotranspiration data (1925–2010 according to Šiauliai WS and 2011–2015 according to Rėkyva WS).

Pearson correlation coefficient was used to evaluate relations between the hydrometeorological parameters and the indicators of the moisture status in Rėkyva raised bog.

The reconstructions of water table fluctuations (RWT) were made in four areas of the raised bog corresponding to water table measuring wells: RWT1 and RWT2 – at the semi pristine part of raised bog in the Rėkyva Lake catchment, and RWT3 and RWT4 at the drained peat harvest area catchment. The mean annual water table in the raised bog was obtained from mean monthly water level records of Rėkyva Lake, net precipitation and mean annual river runoff. Thereafter, we tested the suitability of reconstructing bog-water table using lake levels affected by anthropogenic influence.

The reconstructions of water table fluctuations in the raised bog were based on linear or logarithmic regressions between mean monthly indicators from period 2011–2015: (i) water table in WTWs and Rėkyva Lake water level (LWL) – reconstructed water table $RWT_L$; (ii) water table in WTWs and net precipitation (NP) – reconstructed water table $RWT_{NP}$; (iii) water table in WTWs and runoff of Dubysa ($Q_D$) – reconstructed water table $RWT_{QD}$. The linear regressions between mean monthly bog and lake water levels and accumulated NP for different time scales (*k* number of months) from 2011 to 2015 were also analysed on purpose to find the best relationships for reconstruction of water table ($RWT_{NPk}$). The water table fluctuations in 2016–2017 at four study sites of raised bog were reconstructed in accordance with estimated linear regressions and compared with measured values.

Possible relations between tree growth and hydrometeorological conditions were studied from comparisons between TRW data and annual precipitation, annual net precipitation, and mean annual Dubysa River runoff separately. These comparisons were also made separately for each period with different anthropogenic impacts on Rėkyva Lake (no/minimal impact during 1925–1938 and 1979–2012; strong impact during 1939–1978; Table 1).

The relatively short, five-year simultaneous data series of water table changes make the verification of a long-term retrospective analysis of water table changes difficult. Therefore, the relationships between various indicators' (lake water level, bog water table, net precipitation, runoff) monthly averages were calculated. In this way, correlations between > 50 analysed pairs were obtained. However, one complicating factor is that the water table and peat surface elevation data represent a period when the lake level was one of the highest during the observation period. On the other hand, the anthropogenic influence on the lake water system was insignificant, similar to the period until late 1950s. For these reasons, the following assumptions were made in the modelling of water level changes in Rėkyva Lake and the raised bog:

1. WTW1 and WTW2 reflect changes in semi-pristine part of raised bog, where typical vegetation of open raised bogs prevails. The water table and peat surface in this area varies only due to changes of hydrometeorological conditions.
2. WTW3 and WTW4 reflect changes in drained part of raised bog. Upper peat layer near WTW4 is subsided and vegetation of degraded raised bog prevails. The water table and peat surface in this area varies due to drainage and changes of hydrometeorological conditions.
3. Rėkyva Lake water level fluctuations depend only on hydrometeorological conditions from last decade of 20th century.

## 3. Results and interpretations

### *3.1. Water-level fluctuations in the seepage lake as indicator of moisture status in raised bog*

The Rėkyva Lake and the raised bog are both located in the same catchment and form the internal parts of the wetland complex. The lake level therefore influences water storage in the entire raised bog. The monitoring period of the lake level is, however, significantly longer than the monitoring series of the raised bog water table. Lake water level data were therefore used to estimate water storage in the raised bog.

Water table fluctuations in the raised bog for the periods 1951–1978 and 2004–2017 have been reconstructed using water-level monitoring data from the Rėkyva Lake. The largest oscillations of water levels in the lake have been measured in 1951 (0.58 m) and 1959 (0.45 m, Fig. 2) when the controlled height weir in the lake effluent ditch was installed and large amounts of water were released from the lake. Low annual water levels observed during these years could result from both climatic factors and the artificial regulation of the water level. The extreme conditions recorded for 1951 could be linked to the climate, as large amount of precipitation in late 1950 were followed by a cold winter and thick snow cover, which combined resulted in extremely high water levels in the lake and raised bog in the first half of 1951. The lowest amount of precipitation during the period 1925–2004, however, was also recorded in 1951, but during the warm end of year, which resulted in a shift towards an extremely low water level in the lake and the raised bog. The radial growth of trees shows TRW values below average for the years 1950 to 1952, but does not indicate extremely

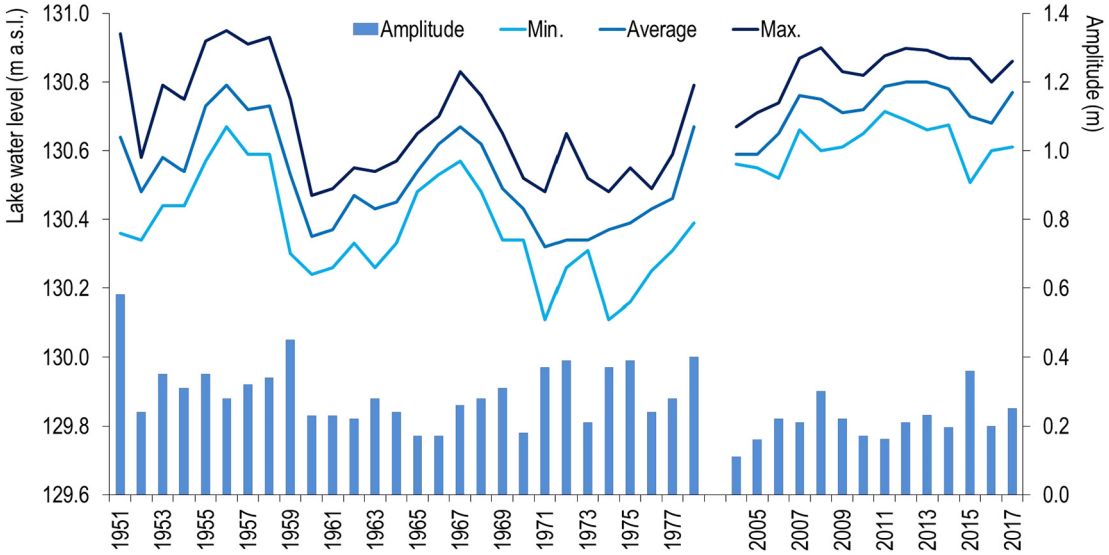


**Fig. 2.** Rėkyva Lake's water level during the period of 1951–2017 (incomplete year measurement in 2004; there was no gauging station in Rėkyva Lake in 1979–2003).

severe conditions in 1951, maybe as a result of the rapid changes towards warmer and drier condition during the main part of the growing season of the trees. The large oscillations of the lake water level in 1959 are the result of extremely low annual precipitation and artificial regulation, as the lake effluent weir was reconstructed in this time.

The period 1958–1971 was relatively dry (Fig. 2) and the lowest recorded water level in the Rėkyva Lake was measured in 1971. This period is characterized by low precipitation and high air temperatures (mean annual temperature was 0.8 °C higher than the climatological normal). Especially low amounts of precipitation, 44% lower than the climatological normal, can be observed for the summer of 1971. Moreover, below-average amounts of precipitation (8–12%) were recorded between 1968 and 1971. The relatively dry conditions recorded during the 1970s may also explain the strong radial tree growth observed at the peat bog during this period (Edvardsson et al., 2015a). Increased annual tree growth and colonization has also been detected at other peatland complexes in Lithuania (Edvardsson et al., 2015b) and Estonia during this period (Smiljanić et al., 2014). Therefore, we interpret the hydrological conditions during the 1970s at these Baltic peatlands as dry and with low water tables (Charman et al., 2004; Smiljanić et al., 2014; Edvardsson et al., 2015a; Taminskas et al., 2018).

### 3.2. Relationship between water level in the raised bog and lake

In both the raised bog and the lake, the maximum annual water levels were recorded between December and April. In some years, however, substantial differences exist in the timing between the maximum water level in the lake and raised bog. This asynchronism may be explained by the slow hydrological response in the system and the existence of lag effects, which often have been recorded in raised bogs (Waddington et al., 2015). Different local melting conditions of snow and ice and differences in seasonal frost regimes are other factors influencing hydrological conditions at the raised bog. By contrast, close relations are observed between the dates of the lowest water level in the lake and raised bog, especially in 2011, 2012, 2013 and 2017.

Water-level minima in both the lake and the bog were unsurprisingly observed after periods of intensive evapotranspiration during the summer or autumn months. By contrast, the highest water table in the bog was usually observed in late winter and early spring, while the highest lake water level usually occurred some weeks later in the middle of spring.

The annual amplitude of water level fluctuation (2011–2017) was 0.2 to 0.41 m in the semi-pristine raised bog (WTW1 and WTW2), 0.17 to 0.33 m in the drained part of raised bog (WTW3 and WTW4), and 0.17 to 0.36 m in the lake. Water tables fluctuated from 0.08 m to 0.50 m (WTW1) and from 0.13 m to 0.52 m (WTW2) below the surface in the semi-pristine, and from 0.16 to 0.53 m (WTW3) and 0.14 m. to 0.55 m (WTW4) below the surface in the drained parts of the raised bog.

Synchronous water-level fluctuations were observed in the raised bog and Rėkyva Lake in 2011–2017. Correlation coefficients between the mean monthly Rėkyva Lake water level and raised bog water table are from 0.654 (WTW4) to 0.923 (WTW3), whereas the correlation coefficient between water tables in wells are from 0.722 (WTW3/WTW4) to 0.974 (WTW1/WTW2) (Table 2).

The water level in the lake and the raised bog mainly depends on changes in precipitation and evapotranspiration – factors that should be close to identical over the entire wetland area. On the other hand, local disparities can be observed, especially between water table fluctuations in the lake and the raised bog, which determine individual different variations of annual water level amplitude and trends. These differences were most notable during the winter and early spring, as well as during periods following heavy rainfalls.

Relationships between the mean monthly Rėkyva Lake water level and the mean monthly water table of four WTWs in period 2011–2015 are statistically significant ($p < 0.0001$). Linear regression equations (Table 3) were used to reconstruct the mean monthly water table of WTWs in 2016–2017. Residuals vary from −0.06 m to +0.18 m when reconstructed and measured mean monthly water tables are compared, and reach highest values in WTW4. Quite high residuals found in other WTWs during the periods of the lake water level rising. Such distribution of residuals may be related to the fixed height weir installed on the outflow of Rėkyva Lake. When the rising lake water reaches the edge of

**Table 2**
Correlation coefficients between the mean monthly Rėkyva Lake water level and raised bog water table in 2011–2017 ($p \leq 0.0001$).

| | Lake | WTW1 | WTW2 | WTW3 | WTW4 |
|---|---|---|---|---|---|
| Lake | n | 0.860 | 0.823 | 0.923 | 0.654 |
| WTW1 | 0.860 | n | 0.974 | 0.943 | 0.814 |
| WTW2 | 0.823 | 0.974 | n | 0.898 | 0.844 |
| WTW3 | 0.923 | 0.943 | 0.898 | n | 0.722 |
| WTW4 | 0.654 | 0.814 | 0.844 | 0.722 | n |

**Table 3**
Relationship between the mean monthly lake water level and raised bog water table in 2011–2015 ($p < 0.0001$).

| Linear regression equation | Correlation coefficient |
|---|---|
| $RWT1_L = 0.929 \times LWL + 10.18$ | 0.910 |
| $RWT2_L = 0.804 \times LWL + 28.56$ | 0.879 |
| $RWT3_L = 0.876 \times LWL + 19.05$ | 0.950 |
| $RWT4_L = 0.723 \times LWL + 38.14$ | 0.798 |

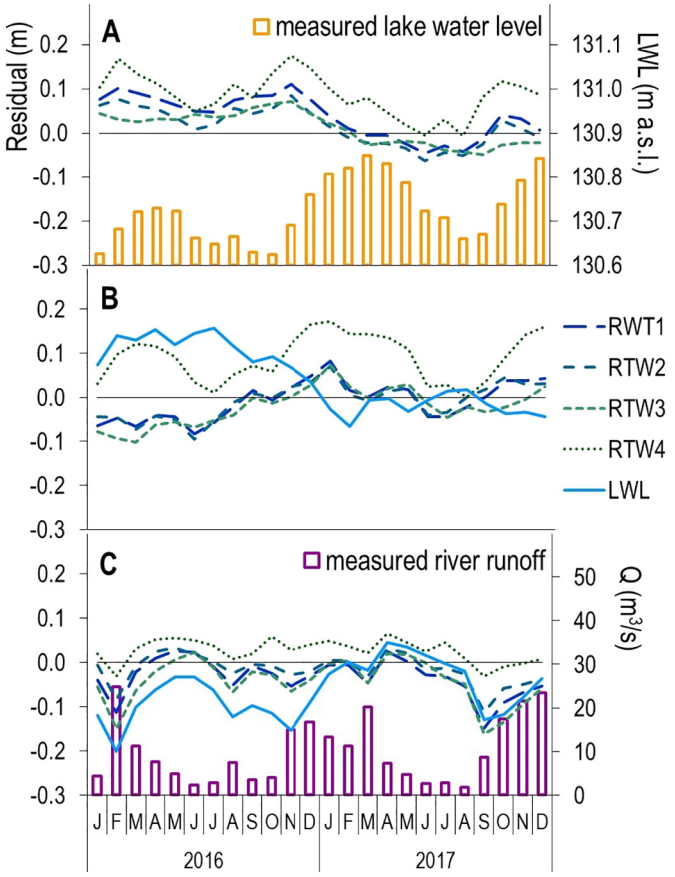


**Fig. 3.** Residuals of water levels reconstructions based on different indicators: A – Rėkyva Lake water level, B – net precipitation, C – Dubysa River runoff.

the weir it starts to overflow and water level stops to rise. Meanwhile, the water table in the bog is still rising. The measuring data of WTW4, located farthest from the lake, shows the slightest response to the lake's water level changes resulting in the maximum residuals (Fig. 3A).

### 3.3. Relationship between net precipitation and water level in the raised bog and the lake

The correlations between mean monthly water table in the raised bog, lake water level and accumulated NP for different time scales (from 1 to 10 months) in 2011–2017 have a high statistical significance ($p < 0.0001$). The highest correlations were observed between mean monthly depth of water table in semi pristine raised bog and accumulated NP of 4–5 months NP. Moderate correlation was obtained between the mean monthly lake water level and the accumulated NP of six months (Table 4). This is likely due to hydrological differences in the water balance between the raised bogs and the lake. While water table lowering in the lake is mainly are controlled by evaporation and surface runoff, it is mainly driven by direct precipitation and evapotranspiration in the raised bog. Linear regression equations (Table 5) were used

**Table 4**
Correlation coefficients between the mean monthly water level at the different monitoring sites and amount of net precipitation in 2011–2017 ($p \leq 0.0001$, bold values – $p \leq 0.00001$).

| Amount of months | Monitoring site | | | | |
|---|---|---|---|---|---|
| | Lake | WTW1 | WTW2 | WTW3 | WTW4 |
| 1 | 0.130 | 0.303 | 0.366 | 0.197 | 0.439 |
| 2 | 0.341 | **0.587** | **0.649** | 0.426 | **0.650** |
| 3 | **0.488** | **0.694** | **0.749** | **0.607** | **0.727** |
| 4 | **0.597** | **0.756** | **0.806** | **0.709** | **0.761** |
| 5 | **0.663** | **0.760** | **0.766** | **0.755** | **0.733** |
| 6 | **0.688** | **0.712** | **0.729** | **0.720** | **0.660** |
| 7 | **0.673** | **0.638** | **0.673** | **0.671** | **0.547** |
| 8 | **0.619** | **0.539** | **0.590** | **0.583** | 0.421 |
| 9 | **0.558** | 0.448 | **0.510** | **0.553** | 0.307 |
| 10 | **0.489** | 0.378 | 0.430 | 0.477 | 0.228 |

**Table 5**
Relationship between the mean monthly lake water level, raised bog water table and accumulated net precipitation for different time scales in 2011–2015 ($p < 0.0001$).

| Linear regression equation | Number of month | Correlation coefficient |
|---|---|---|
| $LWL_{NP6} = 0.0007 \times \sum_{k=1}^{6} NP + 130.69$ | 6 | 0.637 |
| $RWT1_{NP5} = 0.0007 \times \sum_{k=1}^{5} NP + 131.56$ | 5 | 0.766 |
| $RWT2_{NP4} = 0.0007 \times \sum_{k=1}^{4} NP + 133.62$ | 4 | 0.822 |
| $RWT3_{NP5} = 0.0006 \times \sum_{k=1}^{5} NP + 133.47$ | 5 | 0.798 |
| $RWT4_{NP4} = 0.0007 \times \sum_{k=1}^{4} NP + 132.66$ | 4 | 0.804 |

to reconstruct the mean monthly water level in Rėkyva Lake and WTWs in 2016–2017; residuals vary from −0.10 m to +0.17 m (Fig. 3, B).

Water table fluctuations in the raised bog and Rėkyva Lake were reconstructed for the period 1925–2017 using the relationships between mean monthly water table levels and the accumulated NP of five months. The reconstruction shows a minor fluctuation of the water table in the raised bog, from 0.14 m to 0.30 m below the surface in the semi-pristine (RWT1-$2_{NP}$), and from 0.25 m to 0.37 m in the drained part (RWT3-$4_{NP}$; Fig. 4). According to the 2011–2017 monitoring, mean annual water table fluctuations ranged between −0.13 m and −0.30 m in the semi-pristine and from −0.23 m to −0.35 m in the drained part of the raised bog.

According to the NP reconstruction of water table fluctuations, eight extremely dry years, namely 1938, 1951, 1959, 1971, 1976, 1996, 2005 and 2006, occurred during the period 1925–2017. The water table in the semi-pristine raised bog was 0.25 m below the bog surface and in the drained areas – 0.32 m below the bog surface. Opposite conditions were recorded in 1926, 1928, 1933, 1956, 1980, 1981, 1998, 2007, 2013, 2014 and 2016, when extremely wet conditions were recorded. During these eleven years, the water table in the semi-pristine raised bog was < 0.14 m below the bog surface, whereas the corresponding water table was −0.25 m in the drained areas.

### 3.4. Relationship between river runoff and water table in the raised bog and the lake

Water table fluctuations in wetlands may interact with water runoff processes and hydrology in adjacent catchments. The understanding of groundwater and surface water interactions therefore requires precise knowledge of the location of wetlands within the landscape (Price et al., 2005). The Rėkyva wetland complex is located in the watershed of three rivers, namely the Dubysa, Venta, and Mūša Rivers (Fig. 1). There are naturally interactions and dependencies between runoff in these rivers and water table variations in the Rėkyva wetland complex.

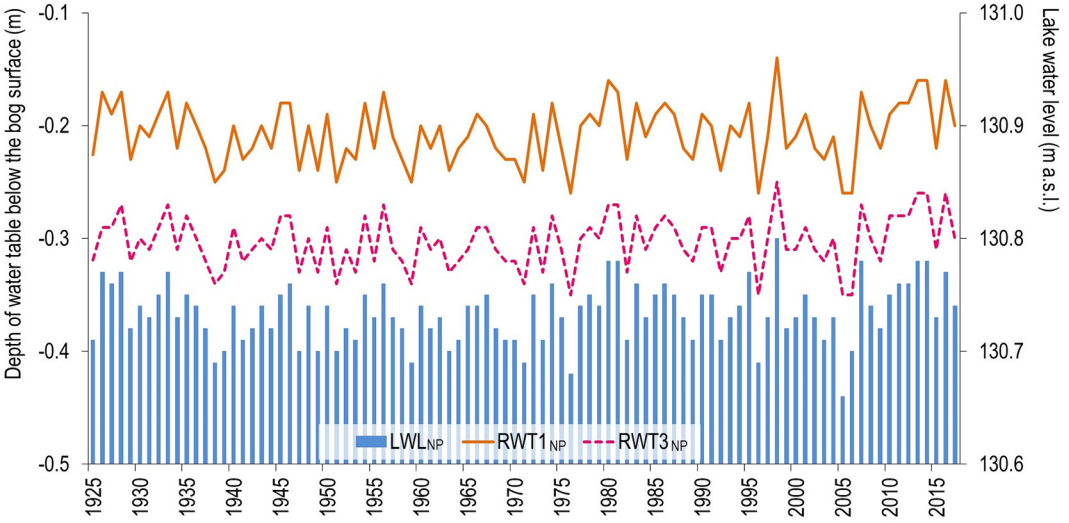


**Fig. 4.** The mean annual depth of raised bog water table (based on surface elevation according to 2017 measurements) and mean annual lake water level, reconstructed according to accumulated NP.

Taking into consideration the coefficient of determination and duration of water measurements, the Dubysa River runoff data was selected to reconstruct water table changes in the Rėkyva wetland complex. The Dubysa river runoff data covers the same period as the meteorological data series (1934–2017), which allows for estimates of water table fluctuation in the raised bog with two different methods, (i) river runoff and (ii) net precipitation. Significant coefficients of determination between peatland tree growth and river runoff have previously been reported in a study from Sweden (Edvardsson and Hansson, 2015). The present study strengthens our assumption that agreement exists between hydrological conditions in peatlands and river runoff. River runoff data might also show a more regional signal than the meteorological data from a single station.

The strongest coefficient of determination was obtained between monthly raised bog water tables (WTW4) and monthly water runoff in the Dubysa River (linear – 0.667, logarithmic – 0.846). The relation between the two variables is better modelled by a logarithmic relationship, although the linear function is highly significant for the data from the Dubysa River as well ($p \leq 0.0001$).

Relationships between mean monthly water levels in Rėkyva Lake and raised bog and mean monthly Dubysa River runoff in 2011–2015 were analysed. Highest coefficients of determination obtained between river runoff and water table in WTW2 and WTW4, and lowest – between river runoff and Rėkyva Lake water level (Table 6). Logarithmic regression equations (Table 6) were used to reconstruct the mean monthly water level in Rėkyva Lake and WTWs in 2016–2017. Residuals of reconstruction vary from −0.20 m to +0.08 m, highest values of residuals reached when comparing reconstructed and measured lake water level. Quite high residuals found in raised bog WTWs especially during periods of high river runoff (February of 2016 and September–December of 2017) (Fig. 3C). It may be related to limited water accumulation capacity of the lake and the raised bog.

**Table 6**
Relationship between the mean monthly lake water level, raised bog water table and runoff of Dubysa River in 2011–2015.

| Logarithmic regression equation | Determination coefficient |
|---|---|
| $LWL_{QD} = 0.079 \times ln\,Q_D + 130.63$ | 0.544 |
| $RWT1_{QD} = 0.0867 \times ln\,Q_D + 131.48$ | 0.625 |
| $RWT2_{QD} = 0.0782 \times ln\,Q_D + 133.54$ | 0.640 |
| $RWT3_{L} = 0.0752 \times ln\,Q_D + 133.40$ | 0.579 |
| $RWT4_{L} = 0.0893 \times ln\,Q_D + 132.56$ | 0.846 |

The bog and lake water level reconstructions based on NP and Dubysa River runoff show synchronous water level changes, although the mean annual water level is lower according to the NP reconstruction. The biggest discrepancies between two reconstructions occur in the years with the extremely low or extremely high runoff of Dubysa River, in 1954 and 2017, respectively (Fig. 5). This might be because PET usually is a bit higher than the actual evapotranspiration. The $RWT_{NP}$ might therefore be lower than the actual level of the water table.

The correlation coefficient between the raised bog water table reconstructions based on the Dubysa river runoff and reconstructions based on NP is from 0,699 (WTW4) to 0.737 (WTW1) ($p \leq 0.001$) for the period 1925–2017. The correlation coefficient between the mean monthly raised bog water table measured in WTWs (2011–2017) and $RWT_{NP}$ is from 0.651 (WTW4) to 0.753 (WTW2) ($p > 0.01$), whereas the correlation between the measurements and $RWT_{QD}$ is from 0.622 to 0.933 (WTW4) ($p < 0.01$). However, relationships are weaker between the mean monthly measured Rėkyva Lake water level and the reconstructions based on NP and river runoff: correlation coefficient reaches 0.400 ($p < 0.1$) when analysing NP based reconstruction, and 0.583 ($p < 0.05$) when analysing runoff based reconstruction. The river runoff data therefore appear to be the best suited to reconstruct water table fluctuations in the raised bog. These results, as well as the correlation tests presented by Edvardsson and Hansson (2015), indicate that monitored river discharge data has the potential to be a good indicator of the hydrological conditions in raised bogs within the same catchment area.

Some discrepancies exist between the highest and lowest reconstructed water table level based on net precipitation ($RWT_{NP}$) and on Dubysa runoff data ($RWT_{QD}$). According to net precipitation, the lowest water levels occurred in 1951, 1996, and 2005, whereas the reconstruction using the Dubysa runoff suggests 1937, 1938, 1939, 1954, 1969 and 2006 as the most extreme years. The highest water tables, according to net precipitation, were in 1933, 1980, 1981, 1998, 2013, and 2016. Similar results were obtained according to the reconstruction using the Dubysa runoff (1980, 1981 1998 and 2007 and 2017).

Reconstructions of water table fluctuations during period 1925–2017 show at least two periods with various hydroclimatic conditions in the Rėkyva wetland complex. Relatively dry conditions prevail from 1937 up to 1976, and then fallowed wetter period (Fig.7).

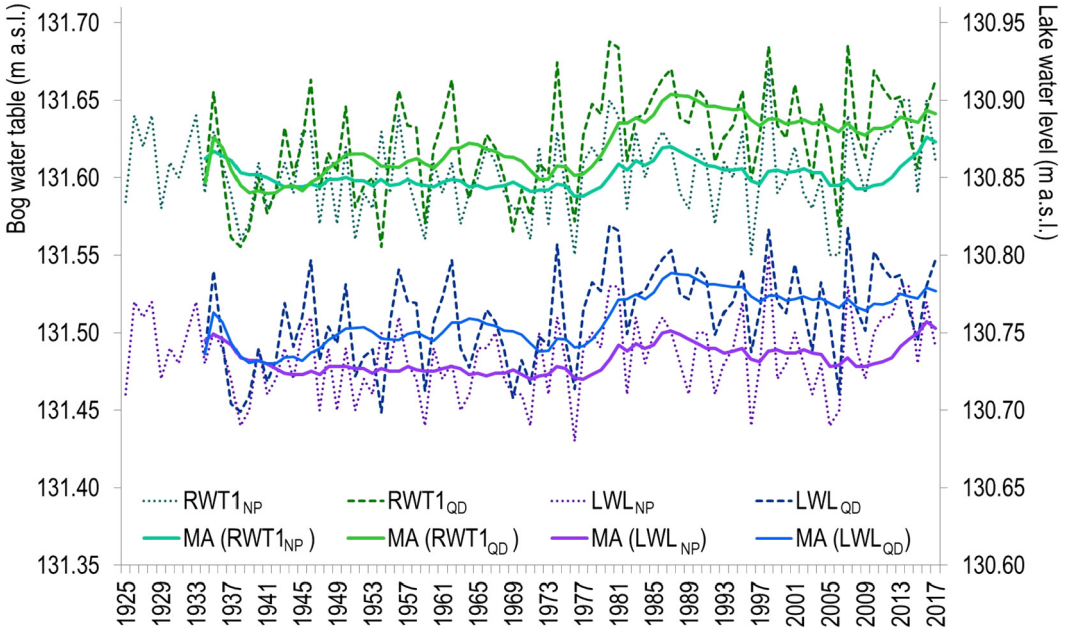


**Fig. 5.** The mean annual water table in the raised bog and Rėkyva Lake, reconstructed according to net precipitation and Dubysa River runoff and 10-year moving averages (MA).

### 3.5. Relationship between hydrometeorological conditions and tree growth

Comparisons using TRW data and hydrometeorological indicators (P, NP and $Q_D$) over the period 1934 to 2012 show weak, but significant ($p < 0.05$) correlation between TRW data and Dubysa River runoff data only. In the remaining cases, the relation was not reliable, and for the period of artificial lake-level regulation (1939–1978), all tests between annual TRW and hydrometeorological indicators was insignificant ($p > 0.1$). For the period with unregulated lake levels (1925–1938 and 1979–2012), however, significant relationships were obtained between the series. Weak positive correlations are seen between the TRW data and annual precipitation, net precipitation, and Dubysa River runoff.

Positive correlation ($p < 0.1$) was obtained between TRW and annual net precipitation during periods of strong radial tree growth (TRW ≥ +1SD, Fig. 6). Such periods were recorded in 1869–1873, 1915–1925, 1941–1948, 1972–1978, and 1995–1998. These periods are associated with relatively dry conditions, low water tables and low river runoff. Meanwhile, negative correlations ($p < 0.05$) between TRW and annual net precipitation are observed during periods associated with depressed growth (TRW ≤ −1SD, Fig. 6). These periods took place 1855–1861, 1882–1886, 1889–1901, 1931–1938, and 1988–1993, and correspond with the moist conditions and high river runoff. A negative correlation is logic as wetter conditions cause harsher growth conditions for the trees at the peat bog. Positive correlation ($p < 0.05$) was found for the years showing intermediate tree growth (−1SD < TRW < +1SD, Fig. 6). Although annual precipitation, net precipitation, and rivers runoff can vary over a wide range during years showing depressed tree growth, multiannual mean (4–7 previous years) of these hydrometeorological indicators is usually lower than average of the entire measurement period.

Precipitation, net precipitation and mean river runoff are closely linked to wetness and water storage of the wetland. In the Rėkyva wetland complex, these indicators and TRW of Scots pine vary in a similar manner, although there are years (for example 1965–1966, 1990–1991) when trends of changes are opposite (Fig. 7). However, analysing relationships between TRW and hydrometeorological parameters, a negative correlation was obtained. Weak negative correlation ($p < 0.05$) was obtained between TRW and the multiannual (5–7 years) mean precipitation, multiannual (4–7 years) mean net precipitation, and multiannual (6–7 years) mean Dubysa river runoff (Table 7).

## 4. Discussion

Several studies show that usually water table seldom drops lower than 0.3 m below the peat surface in semi pristine raised bogs (Balyasova, 1974; Povilaitis et al., 2011). Our results show water level shifts between 0.08 and 0.52 m in semi-pristine, and between 0.16 and 0.55 m below the surface in the disturbed part of raised bog during the years 2011 to 2017. The lowest water levels were observed in one year 2015 in all the study sites, while highest water levels were recorded during different years in each of our study sites. Such distribution may show that the minimum water table is determined by regional, and the maximum – by local conditions.

Our study shows that case and effects of hydrological changes in wetland complexes are difficult to understand, and that disturbances from human activities may cause major difficulties in reconstructing hydrological shifts in the past. Despite this, several linkages between hydrological indicators such as the water level in the lake and the raised bog, as well as river runoff within the studied catchment area were detected, which allow for a reconstructions of hydrological conditions in the Rėkyva wetland complex by combining the different data series. Not surprisingly, precipitation, temperature, and evaporation were found to influence the hydrology within the wetland complex. The factors that govern the hydrology were also found influencing the radial growth of moisture sensitive wetland trees, even though the growth variability of the trees sometimes was difficult to interpret due to lag-effects and anthropogenic activities (e.g. ditching and regulation of the water level in the lake). The combination of all used meteorological, monitoring, and tree ring records, however, enabled us to study and reconstructions of water level changes in both the raised bog and the seepage lake located in the catchment area of the Rėkyva wetland complex. However, records on land-use changes such as drainage and regulation of lakes are needed as the climatic signal was found to blurred or even erased during periods with substantial anthropogenic influences. The Rėkyva Lake is therefore not an appropriate indicator of dry and wet conditions in entire Rėkyva wetland complex, but

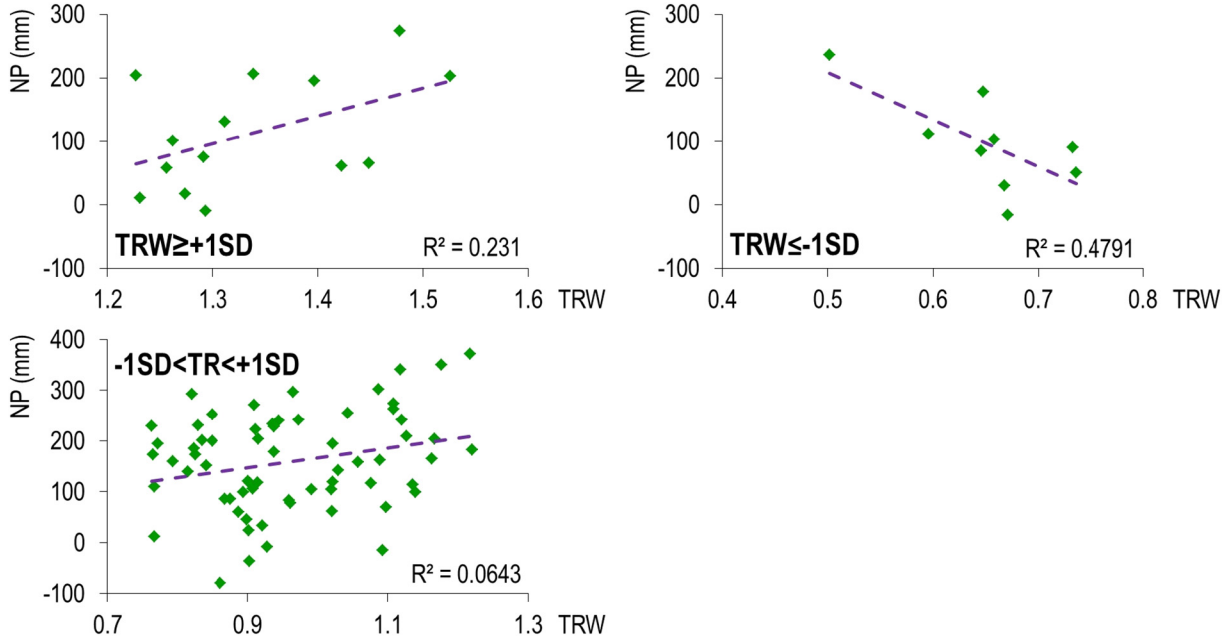


**Fig. 6.** Correlation between tree-rings and net precipitation during periods of strong tree growth (TRW ≥ +1SD), depressed tree growth (TRW ≤ −1SD) and normal tree growth (-1SD < TRW < +1SD).

adequately reflects hydrological conditions of the lake catchment.

Our study from the Rėkyva wetland complex shows that mean monthly water level in different parts of the wetland (e.g. lake or raised bog) were significantly correlated and were thereby regarded as suitable complement for each other and useful for reconstruction of water table fluctuations in the wetland complex. Water table fluctuations in both the raised bog and the lake proved to be depending on meteorological conditions, even though slower hydrological responses were observed in the bog compared to the lake. Significant correlations were found between the mean monthly water level in the lake and raised bog when the amounts of four-five (raised bog) and six (lake) months' net precipitation values were used. A significant correlation was also found between mean monthly water table in the raised bog and mean monthly river runoff data. River runoff data is, therefore, believed to be a suitable indicator for water storage in peatlands sharing the same catchment area. River runoff from considerably larger catchment areas, however, may not always reflect the local scale water regime changes in the wetland complex, neither local anthropogenic water level regulations.

**Table 7**
Correlation between TRW and multiannual mean of P, NP, $Q_D$ and $Q_N$.

| Number of years | *P* | | *NP* | | $Q_D$ | |
|---|---|---|---|---|---|---|
| | *R* | *p* | *R* | *p* | *R* | *p* |
| 1 | 0.097 | > 0.1 | 0.106 | > 0.1 | 0.226 | < 0.05 |
| 2 | 0.032 | > 0.1 | 0.039 | > 0.1 | 0.179 | > 0.1 |
| 3 | −0.084 | > 0.1 | −0.073 | > 0.1 | 0.122 | > 0.1 |
| 4 | −0.191 | < 0.1 | −0.279 | < 0.05 | 0.014 | > 0.1 |
| 5 | −0.279 | < 0.05 | −0.271 | < 0.05 | −0.073 | > 0.1 |
| 6 | −0.365 | < 0.01 | −0.375 | < 0.001 | −0.307 | < 0.01 |
| 7 | −0.393 | < 0.001 | −0.413 | < 0.001 | −0.280 | < 0.05 |

Analyse of residuals between measured and reconstructed by different indicators Rėkyva wetland water table allows to evaluate the possibilities of applying these indicators to the retrospective assessment of the raised bog moisture variations. Reconstruction based on Rėkyva Lake water level showed highest residuals at the drained part of raised bog (WTW4). High residuals at all study sites in 2016 were probably

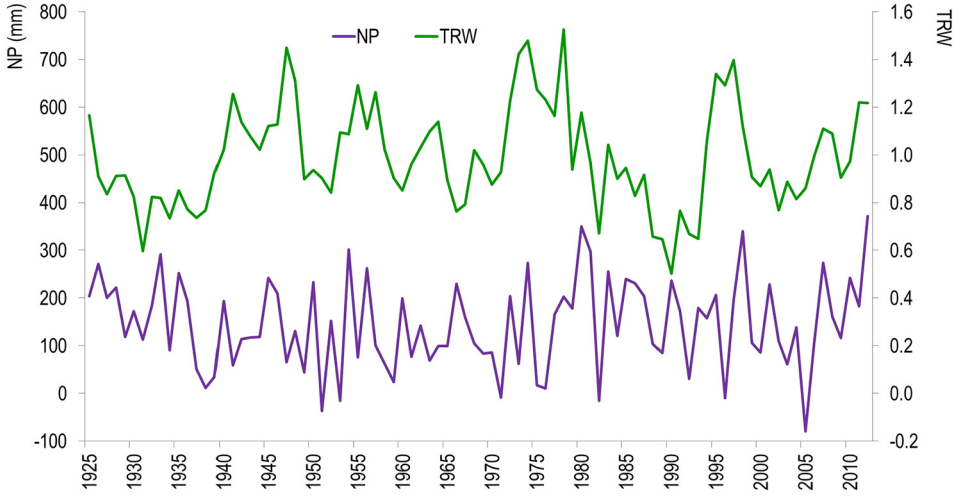


**Fig. 7.** Annual net precipitation (NP) and tree-rings width (TRW) in Rėkyva raised bog.

caused by repair of the effluent ditch and the installation of temporary dam (Fig. 3A).

Reconstruction based on net precipitation also gave high residuals at the drained part of raised bog (WTW4). Positive residuals during almost all months of the reconstruction can be caused by peat layer subsidence near the edge of drained bog: subsided peat disturbs the outflow from other parts of the raised bog. Higher residuals received at all study sites during the winter season can be due to snow cover and/or seasonal frost (Fig. 3B). Reconstruction of Rėkyva Lake water level showed the highest residuals and difference between two years of reconstruction. This may be related to the effect of temporary dam.

Reconstruction based on Dubysa River runoff showed quite low residuals in all WTWs. More significant negative residuals obtained during the flood rising can be related to the outflow from raised bog disturbed by subsided peat and the relatively lower water reserves in the wetland complex during this period comparing with the other parts of river catchment. Highest residuals between measured and reconstructed by $Q_D$ water levels in Rėkyva Lake can be determined by the same reasons as in previous cases.

The radial growth of the pine trees growing in the natural part of the raised bog was linked to the hydrological conditions at the site. Strong radial tree growth (TRW ≥ +1SD) was observed during periods associated with relatively low water tables in the entire wetland complex and low annual river runoff. Meanwhile, depressed tree growth (TRW ≤ -1SD) was observed during moist periods when the water level was high in the wetland, especially the bog areas, and the annual river runoff was clearly above average. The compilation of our data series show several short term and some essential shifts over the past 100 years, and since the 1940s to 1970s the wetland has gradually become drier. The hydrological changes in the Rėkyva wetland complex, especially the changes linked to climate, were often confirmed by the growth variability of the local trees as well as local to regional meteorological and climatic data series.

Correlation between TRW of raised bog pines and hydrometeorological indices can be both positive and negative. A positive correlation between annual precipitation, annual net precipitation and TRW may be due to higher amounts of nutrients seeping with precipitation into the water unsaturated zone where the root system of the trees is located. This might be a factor influencing tree growth when dry conditions prevail. Negative correlation is related to several years' period of excess moisture in raised bog and indicates that the several consecutive wet years inhibit the growth of wetland pines. This may be due to the long-term interference of oxygen and nutrient access to the root zone (Edvardsson et al., 2016).

The highest bog water table was in 1998, when the water table was 0.14 m below the bog surface in the pristine part and 0.25–0.28 m below the surface in the drained part of raised bog. The highest lake level was also during this year. Opposite conditions were in 2005, 1996, and 1976 respectively, when the bog water level was 0.26 m below the surface in the pristine part of the bog and 0.35 m below the surface in the drained part (Fig. 5). Strong radial tree growth, visualised as growth rings wider than +1 standard deviation above average can be observed for 1996 and 1976, which indicate dry bog surface conditions (Edvardsson et al., 2015a). For 2005 and 1998, however, no unusual growth patterns of the trees could be detected.

The low lake water level was in 1938, 1959, 1971, 1976, 1996 and 2005, minimum peak – in 2005 when the lake level was 130.66–130.69 m a.s.l. (Fig. 5). These results are in line with unprecedentedly low water levels at Rėkyva Lake reported in local newspapers for the end of 1938. Strong radial tree growth has been reported for the years 1938–1939, 1971, and 1976 by Pakalnis (1984). For the Rėkyva bog, Edvardsson et al. (2015a) show strong annual tree growth during the 1940s and 1970s. Both studies support the assumption that bog surface conditions were dry during these periods. Observations are in line with the assumption that moisture is a growth-limiting factor in peatlands, and that radial tree growth therefore increase during relatively dry periods (Boggie, 1972; Edvardsson et al., 2016).

These wet and dry phases are in agreement with periods associated with depressed and elevated annual tree growth, respectively, using moisture sensitive trees at the Rėkyva peat bog (Edvardsson et al., 2015a). Wet periods during the late 1800s and in beginning 1900s and drier conditions since the 1950s also match nicely results presented by Hendon and Charman (2004) and Charman (2007). A prolonged period characterized by low water tables has been recorded from 1937 to 1977 in the Rėkyva wetland (Fig. 5). Similar dry phases have been detected in British peatlands, where a trend towards drier mire surface conditions began during the 1920s or 1930s (Hendon and Charman, 2004). Low water levels have also been observed in other Lithuanian raised bogs and lakes during the corresponding period (Kilkus and Vilkelytė, 2011). It should be noted that exceptionally low water levels often were recorded in proxy records from other sites as well, indicating regional climatic influence on the moisture status of the peatlands. Moreover, agreements between phases of extremely low water table were detected in four out of five (in Moor House catchment significant droughts were detected in 1959, 1976, 1984, and 1992) cases when records from British peatlands (Worrall et al., 2006) were compared to our Rėkyva record.

Comparison of reconstructed mean annual water levels in the lake according to NP and the measured mean annual water levels in the lake in 1951–1978 and 2004–2017 reveals three periods with apparent discrepancies, namely 1952–1954, 1959–1978, and 2004–2007 (Figs. 2 and 5). Discrepancies between the reconstructed and measured water levels in 1952–1954 are thought to reflect the influence of uncontrolled outflow through the SE and NE effluent ditches. During the period 1959–1978, the discrepancy is related to controlled outflow from the lake and water abstraction, which increased especially in 1960 when the power station's capacity was increased. It is possible that imprecisions in the monitoring protocol between 2004 and 2007 could have led to data inaccuracy and accordingly explains the differences between the measured and reconstructed water level fluctuations. Under natural conditions, the reconstructed water level is close to the actual values, but for obvious reasons the periods with significant anthropogenic activities show mismatches.

## 5. Conclusions

Retrospective analysis of moisture variations in wetlands can be complicated due to the lack of hydrological monitoring data. It is therefore necessary to look for the indirect indicators of moisture status. If existing, water level of wetland complex's seepage lakes is likely to be good indicators for the reconstruction of the raised bog water table fluctuations. But this can only be in the case the lake's water level fluctuations are pristine. In other case other indicators are more suitable, because the relations between the raised bog and the lake water level are disturbed by anthropogenic factors.

Data of meteorological monitoring from wetland or nearest surroundings are needed to perform reconstruction of the water table fluctuations based on relationships with net precipitation. This indicator is not suitable for reconstruction of conditions in the winter season, and residuals of the drained bog water table reconstruction are quite high. River runoff is not suitable indicator to reconstruct the water table fluctuations in wetland complex during periods of the flood rising, but proved to be suitable for reconstruction of the water table fluctuations during other periods, both in the semi-pristine and drained parts of raised bog.

Reconstructions based on net precipitations and river runoff showed long term dry period in the middle of 20th century.

Relations between tree growth and meteorological parameters are ambiguous. Weak positive correlation detected between TRW and annual indicators of moisture status (river runoff), however negative correlation detected between TRW and multiannual indicators of

moisture status (precipitation, net precipitation, river runoff). It shows that the short term moisture increase has a positive influence on tree growth, while the long term or extremely high moisture excess cause harsher growth conditions for the trees at the peat bog.

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